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Electrically Suspended Gyro (ESG) inertial technology has been applied to the field of inertial positioning and survey during the past few years. The first operational system, designated the IPS-2, was delivered to the U. S. Defense Mapping Agency in September, 1979. Since that time it has undergone extensive field evaluation and has had several software product improvements incorporated. Its current positioning accuracy level was demonstrated at 25-50 cm, RMS, for 4 minute ZUPT intervals on a 35 km course with dual traverses. With 2 minute intervals and single traverses, the system produced 25 cm, RMS, results. These are much better than the DMA specification

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For the DMA application, the IPS-2 was required to output gravity measurement data, both amplitude (or anomaly) and vertical deflection components. It has done this in real time to an accuracy of 4 milli-gals, RMS, and 2 arc-seconds, RMS, in tests at Cheyenne, Wyoming, and Clearwater, Florida. However, much more precise gravity measurement accuracy is desired for future surveys. Therefore, in September, 1980, the U. S. Army Engineer Topographic Laboratories, Ft. Belvoir, Virginia, contracted with Honeywell to evaluate present IPS-2 gravity measurement performance and determine the necessary improvements.

The improved accuracies must be maintained with the system operated along any trajectory in a ground vehicle or helicopter. The most important performance parameter is deflection of the vertical.

This paper reports the results of the gravity improvement study. It addresses hardware, software and operational procedure aspects. Supporting data are provided for the assessment of current performance. On-line and lff-line data reduction and analysis are considered. The rather interesting application of both Kalman filtering (using data up to a current point) and Kalman smoothing (total traverse data processing) is covered and its effectiveness evaluated with supporting computer simulations for the gravity measurement problem. Use of both ZUPT and control point data is considered in the smoothing process. By-products of gravity measurement accuracy improvement are better positioning performance and operational flexibility. These topics are also touched upon in this paper. Hence, it should be of widespread interest to the surveying and geodesy communities.

GEO-SPIN/IPS-2 IMPROVEMENTS
FOR PRECISION GRAVITY MEASUREMENT

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"GEO-SPIN/IPS-2 IMPROVEMENTS FOR PRECISION GRAVITY MEASURMENT"

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ABSTRACT

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The improved accuracies must be maintained with the system operated along any trajectory in a ground vehicle or helicopter. The most important performance parameter is deflection of the vertical.

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in the smoothing process. By-products of gravity measurement accuracy improvement are better positioning performance and operational flexibility. These topics are also touched upon in this paper. Hence, it should be of widespread interest to the surveying and geodesy communities.

1. INTRODUCTION

Six major tasks were performed as part of this study. They were:

Task 1 Evaluate the performance of the existing IPS-2.

Task 2 Determine the error sources in the present system which prevent it from achieving improved performance.

Task 3 Develop an improved system error budget.

Task 4 Determine the system modifications needed to achieve improved performance. These changes may be to hardware, software, operational procedures and/or data processing (on-line or post mission).

Task 5 Perform error analysis and performance simulations to determine the expected performance of the modified system. If the modification cannot be uniquely quantified, parametric analysis shall be performed to determine the range of expected performance. Error analysis and simulation methodology and algorithms were to be validated using system error sources for the existing IPS-2 and achieved performance.

Task 6 The development effort required to incorporate and validate the system modifications was to be determined, including an assessment of development risk.

2. CONCLUSIONS

Significant IPS-2 system error sources were identified which must be reduced to improve the present demonstrated RMS gravity measurement accuracy from 2 arc-seconds (vertical deflections) and 4 milli-gals (anomaly) to projected near term levels of 0.13 to 0.14 arc-second, and 0.64 milli-gal and ultimately to 0.097 to 0.113 arc-second and 0.5 milli-gal. Further reductions in anomaly measurement require additional study and evaluation tests.

The identified error sources are as follows:

1. Hardware
   - Random noise in accelerometer loop measurements
   - Field environmental factors
   - VMU/Gyro crosstalk
   - Gyro TCA cycling
   - Attitude sensitivity

2. Software
   - Accelerometer/VMU error modeling
   - Resolver #1 bias calibration
   - Accelerometer parameter trends

3. Operational Procedures
- Accelerometer/VMU runup-to-runup errors without a pre-mission calibration
- Single vs. multiple traverses
- Sensitivity to traverse termination errors

4. Data Processing - Need for on-line Kalman filter processing and Kalman smoothing at or after closure of each traverse.

All of the identified error sources are reduceable through modifications to the existing IPS-2 system. It is noteworthy that among hardware, software, and operational procedure error sources of the IPS-2, those related to the accelerometers and their control loops are more significant than gyro related errors. This is most likely due to the very low random errors of the Electrically Suspended Gyros used within the IPS-2. Since accelerometer related errors are usually easier to reduce, this offers an encouraging outlook for the IPS-2 accuracy growth potential in gravity measurement and positioning measurement, as well.

A summary of the identified error sources and system modifications which can reduce them is shown in Table 1.

ERROR SOURCE	SYSTEM MODIFICATION
1. Hardware	
A. Random noise in accelerometer loop measurements	• Redesign two accelerometer pulse rebalance electronics assemblies to improve torquer tuning, signal generator tuning, power supply filtering, and torquer pulse patterns.
B. Field Environment factors	• Expand ZUPT measurement period from 20 to 40-60 seconds to average out residual noise.
	• Perform pre-mission accelerometer/VMU static calibration
	• Optimize operator procedures for gravity measurement
	• Improve isolation of IMU from vehicle
	• Shorten ZUPT interval from 4 to 1-2 minutes for positioning accuracy improvement
C. VMU/Gyro crosstalk	• Redesign a PRE board in conjunction with 1A above to transmit accelerometer data on a differential bus using binary coded data
D. Gyro TCA cycling	• Adjust IMU thermal balance using existing models. Also consider thermal modeling in on-line or off-line software
E. Attitude sensitivity	• Same as 1.D, including additional thermal gradient control.

TABLE 1

IPS-2 SYSTEM MODIFICATIONS SUMMARY

ERROR SOURCE	SYSTEM MODIFICATION
2. <u>Software</u>	
A. Acceleromter/VMU modeling	• Add accelerometer scale factor ±g mismatch to the calibration/compensation model, using coefficients from error characterization tests.
B. Resolver #1 bias Calibration	• Adapt the latest procedure developed on the B-52 INS program
C. Acceleromter parameter trends	• Add linear rate and exponential modeling compensation to on-line and/or off-line software
3. <u>Operational Procedures</u>	
A. Accelerometer/VMU runup-to-runup errors	• Same as 1.B. - perform pre-mission static calibration
B. Single vs. multiple traverses	• Apply multiple traverse and/or grid network adjustment as necessary
C. Sensitivity to traverse termination errors	• Perform multiple or extended observations at all control points.
4. <u>Data Processing</u>	
A. Accuracy of current deterministic ZUPT processing and closure software	• Use Kalman filter to perform ZUPTS with least squares preprocessing

TABLE 1 CONT

IPS-2 SYSTEM MODIFICATIONS SUMMARY

3. CURRENT IPS-2 PERFORMANCE EVALUATION

Both field and laboratory tests have been performed to evaluate the current capability of the IPS-2. Positioning accuracies from some of these tests have been reported previously (*Hadfield*, 1980). Gravity data from all of these tests are summarized in Tables 2 and 3. Note the improvement in Table 2 data when initialization and termination errors are minimized.

DATA SOURCE	RMS Deflections V_{DN} (arc-seconds)	RMS Deflections V_{DE} (arc-seconds)	RMS Anomaly ΔG (milli-gals)
• Field Acceptance Test-Cheyenne, Wyo. -with initialization and termination errors	3.7	4.8	11.7
-Minimized initialization and termination errors	1.8	2.1	4.4
• Local Field Test Data (Clearwater, Fla). -with initialization and termination errors	2.3	4.4	5.3
-Minimized initialization and termination errors	1.6	2.7	3.1

TABLE 2

IPS-2 FIELD TEST GRAVITY DATA

DATA SOURCE	RMS Deflections V_{DN} (arc-seconds)	V_{DE}	RMS Anomaly ΔG (Milli-gal)
• Autozupt tests (lab and static van)	0.51	0.48	1.87
• Continuous gravity measurement (Lab)			
-20 second ZUPT duration	0.23	0.29	1.68
-40 second SUPT duration	0.14	0.12	0.79
• Pitch sensitivity tests, 0-30 degrees	2.0	2.0	4-5
• Heading sensitivity tests. 90 degree changes	8-10	8-10	2-5

TABLE 3

IPS-2 LAB AND SPECIAL TEST DATA

A review of Table 2 shows that basic gravity accuracy and repeatability are quite good. However pitch and heading sensitivities are significant and may be factors in the degradation between laboratory and field test results.

4. DATA PROCESSING IMPROVEMENTS

It is felt that the current IPS-2 Zero Velocity Update (ZUPT) and closure software are significant contributors to relative gravity measurement errors. The ZUPT processing calculation performs a curve fit of a sample (nominally 20 seconds) of velocity error samples (8 Hz) and uses the resulting mean velocity error and error slope to update position velocity, and gravity. The closure software performs a linear distribution of terminal position and gravity errors back across the traverse mark points. This ZUPT and closure software was more than adequate for the IPS-2 DMA specification, but will be improved upon for the more accurate gravity measurements considered in this study.

The improved software will utilize the 21 state IPS-2 Kalman filter to provide the ZUPT processing function. Use of Kalman ZUPT processing will reduce the effect of measurement noise on open traverse estimates as well as provide a basis for performing post traverse closure using Kalman smoothing. The smoothing will use a Modified Bryson-Frazier (*Bierman*, 1973) algorithm, thus reducing recording needs. The smoother is planned to be implemented as part of the "on-line" software, but the data which will be recorded can also be processed by a scientific machine off line.

The combination of a high capacity magnetic cartridge type recording device and the 64,000 word (16 bit, 64 bit floating point format) digital computer make the on-line Kalman smoothing and full data recording possible. Complete reprocessing of the initial run using the recorded Inertial Measurement Unit (IMU) output is possible with the IPS-2 because this is a space stable untorqued mechanization with no feedback required from the computer. State error estimates based on position and gravity at the control points as well as estimates based upon zero velocity updates will be processed by the smoother, thus making maximum use of available information.

The Kalman filter will be adjusted using information recorded on the local Honeywell course by using the renavigation feature and many passes through the data. This will avoid costly hardware reruns normally required for Kalman tuning.

5. ERROR BUDGETS

Error budgets were developed for use with the covariance simulation runs described below. Simulations were used for three different purposes:

- Determine IPS-2 error sensitivities.
- Evaluate current IPS-2 gravity measurement accuracy.
- Evaluate modified IPS-2 gravity measurement accuracy.

A "preliminary" budget was used to perform the error sensitivity runs. This was a first cut budget for accelerometer errors and system noise. The gyro drift represents specification level values of these instruments (ESG's) for the airborne navigation application. All three budgets are shown in Table 4.

After examining results of simulations using the preliminary budget and finding accelerometer bias and scale factor to

DESCRIPTION	PRELIMINARY BUDGET VALUE (1σ)	CURRENT BUDGET VALUE (1σ)	MODIFIED BUDGET VALUE (1σ)	UNITS
Accel. SF(3)	5, $\tau = 6$	1.5, $\tau = 6$	1.5, $\tau = 6$	ppm,hours
Accel.Bias(3)	5, $\tau = 6$	1.5, $\tau = 6$	1.5, $\tau = 6$	μg,hours
Accel. Non-orthog.(3)	2, $\tau = \infty$	2, $\tau = \infty$	2, $\tau = \infty$	arc-sec.
G indep. drift (3)	.001, $\tau = \infty$ Rand.Walk = 6×10^{-6}	.0005, $\tau = \infty$ Rand.Walk = 6×10^{-6}	.0005, $\tau = \infty$ Rand.Walk = 6×10^{-6}	deg/hr deg/$\sqrt{hr}$
G dep. drift (7)	.001, $\tau = \infty$ Rand.Walk = 6×10^{-6}	.0005, $\tau = \infty$ Rand.Walk = 6×10^{-6}	.0005, $\tau = \infty$ Rand.Walk = 6×10^{-6}	deg/hr/g deg/$\sqrt{hr}$
G^2 Dep. drift (9)	.0002, $\tau = \infty$	.0002, $\tau = \infty$	.0002, $\tau = \infty$	deg/hr/g^2
Veloc. Rand. Walk	1.4×10^{-4}	1.4×10^{-4}	1×10^{-5}	FPS/$\sqrt{sec}$
ZUPT Veloc. Uncert.	.005	.005	.005	FPS
Grav. Disturb. defl.($sigma^2$) anom.($sigma^2$) charact. dist.	 $(10)^2$ $(50)^2$ 25	 $(10)^2$ $(50)^2$ 25	 $(10)^2$ $(50)^2$ 25	 arc-sec^2 $mgal^2$ n.m.

TABLE 4. IPS-2 ERROR BUDGETS

be large contributors, tests were run to better evaluate the current error in these parameters. Also runup-to-runup gyro drift errors were revised to represent the uncertainty demonstrated during the SPN/GEANS flight test program. The resulting "current" error budget should describe a properly operating IPS-2 system. This budget does not fully describe the hardware since problems with the system were separately identified which produce attitude sensitive platform servo error. This effect is not well represented using a linear covariance simulation program.

Finally an error budget is given (modified budget) which should represent IPS-2 after modifications are made to improve capabilities. Since the improvements to be made will also reduce accelerometer loop noise, the velocity random walk parameter has been adjusted to represent an achievable level of acceleration white noise. This is the only change from the current budget. The effects of heading sensitive servo error should be eliminated by system hardware modifications.

6. SIMULATION RESULTS

In order to perform the simulations required to evaluate IPS-2 error sensitivities, evaluate expected current performance and project performance for a modified system, a Kalman Filter/Smoother covariance simulation program was developed from the existing Honeywell airborne ESG system covariance simulator. The inertial system vertical channel position and velocity states as well as a second order Markov Gravity model were added. A Bryson-Frazier Kalman smoothing mechanization was used. A total of 42 error states were represented.

6.1 Survey Mission Scenario

A Honeywell six degree of freedom trajectory generator program was used to provide the input to the covariance analysis program. The course (White Sands Missile Range) used is based upon Traverse A of reference 1. Single traverses were used except for one run. A helicopter mission was assumed. Nominally, four-minute travel times and one-minute parked periods were used. ZUPT durations varied from 20 to 60 seconds, but 40 seconds was used for most of the runs. The vertical deflection and anomaly models are statistical in nature since a covariance analysis was employed. A second order Markov model of 10 arc-seconds, 50 milligals, and 25 nautical mile characteristic distance was assumed.

6.2 Sensitivity Analysis

The sensitivity analysis was carried out by eliminating one error source at a time and observing the output errors. The results in each case were differenced with the baseline case (with all errors present) by subtracting errors in an RSS fashion. This approach does not produce error sensitivities which can be scaled as might be desired for error budget development. It does, however, produce contributions of all sources for a particular selected budget.

Figure 1 is a typical plot of both the open (Kalman filtered) and closed (Kalman smoothed) gravity survey error for the baseline run. The smoothing uses not only the terminal position and gravity observation data but also all intermediate zero velocity update observations.

Summaries of individual error contributors were produced and appear in Table 5. Although this study addresses relative gravity vector measurement, position survey accuracies have been included for completeness. Examining Table 5, accelerometer bias shows as being the most important contributor to both vertical deflection and gravity anomaly errors. Since this was a north traverse, scale factor error shows up as a major contributor to the north deflection. For IPS-2 with its very low gyro drift rate errors as well as very low gyro random drift rate instability, the gyro contributions to vertical deflection error are small. The remaining significant error source is velocity random walk; this is really due to both accelerometer white noise and high frequency servo error affecting the inner element. Circled numbers in each column show the relative ranking of the top four error sources for each output parameter.

6.3 Effect of Reduced Travel Time

The above runs were made assuming a 4 minute travel time. To see how important this is, a run was made with the travel time reduced to 2 minutes. The park period was kept at 1 minute as before, with 40 seconds data used for the ZUPT period. The results appear in Table 6 (B) (Line A is baseline). These results indicate very little improvement in gravity measurement accuracy. Significant improvement in position survey is obtained as expected.

6.4 Effect of Varied ZUPT Durations

The above runs all use 1 minute park period but only 40 seconds of data were actually examined to perform the ZUPT. In most of the hardware tests a 20 second ZUPT duration was used. Limited tests were made using a 40 second duration. These tests indicated a substantial improvement. To show the expected effect of varied ZUPT durations, simulation runs were made using the "current" budget with 4 minute travel time, one minute park but ZUPT durations of 20, 40 and 60 seconds. The results appear in Table 6 (C,D,E). As experienced with the hardware, there is a significant improvement in gravity and position measurement accuracy by increasing the ZUPT duration from 20 to 40 seconds. The runs show that using 60 seconds

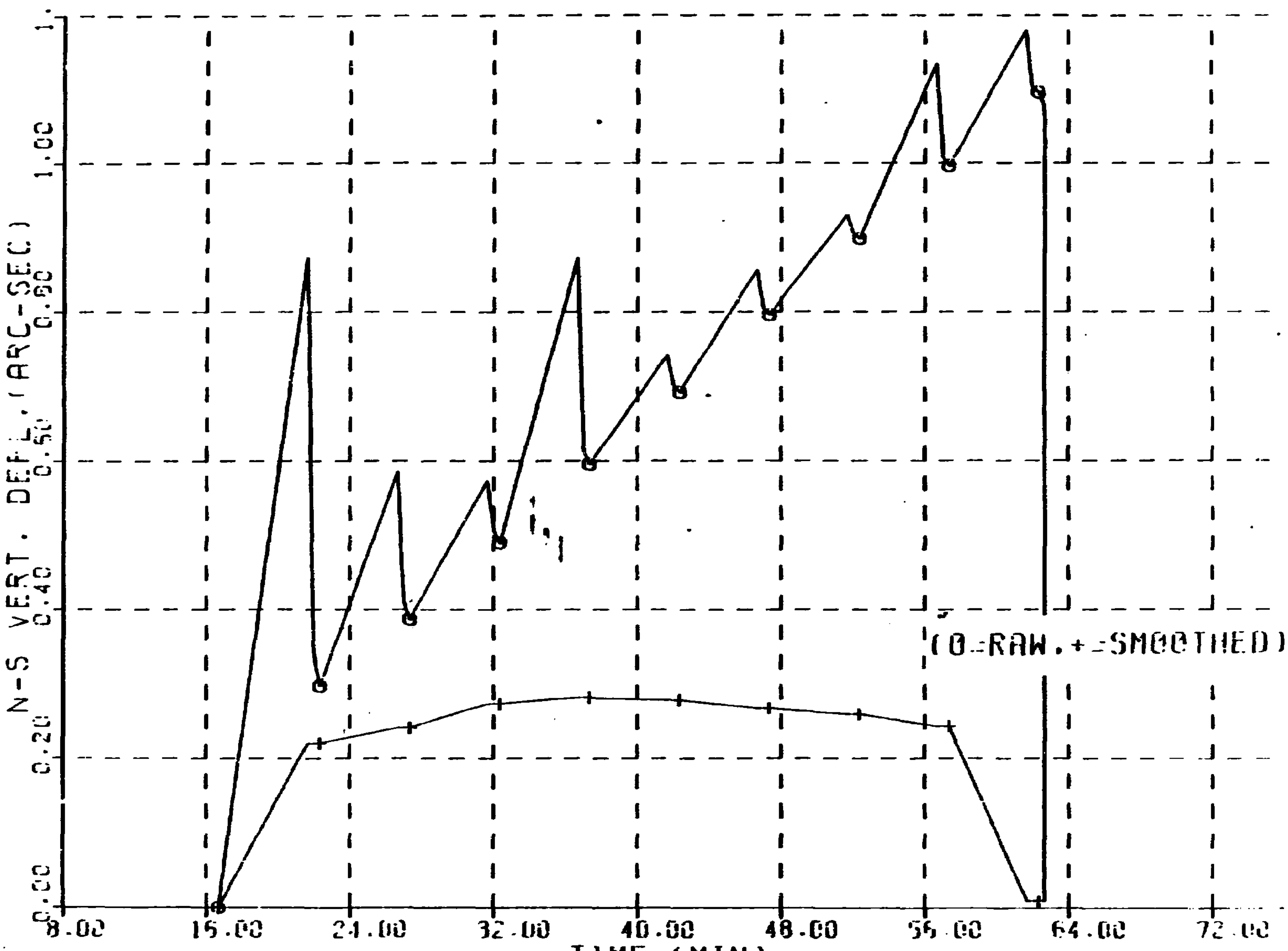

FIGURE 1 BASELINE RUN WITH PRELIMINARY BUDGET

Error Source	No. of Err.	POSITION ERROR SENSITIVITY North Posit. (cm)	East Posit. (cm)	Elev. (cm)	GRAVITY ERROR SENSITIVITY North Vert. Defl. (ε sec)	East Vert. Defl. (η sec)	Anomaly (g mgal)
Accel. Bias	3	7.8 ②	7.1 ②	6.1 ②	.212 ①	.211 ①	.836 ①
Accel. SF	3	4.3	2.8 ④	4.2 ④	.128 ③	.045 ④	.600 ③
Accel. Non-orthog.	3	6.0 ③	1.6	2.3	.045	.040	.240
Gyro Drift							
G Insensitive	3	1.8	2.3	<.1	.071 ④	.018	< .001
G & G^2 Sensitive	15	1.9	2.8 ④	<.1	.069	.030	< .001
Velocity Random Walk	3	10.0 ①	9.2 ①	9.1 ①	.130 ②	.120 ②	.67 ②
ZUPT Null Uncertainty (.005 FPS)	3	5.2 ④	5.0 ③	5.6 ③	.050	.057 ③	.350 ④
RSS		15.8	13.6	13.2	.305	.259	1.303

Note: Circles denote relative ranking of four largest errors.

TABLE 5: IPS-2 POSITION AND GRAVITY ERROR SENSITIVITIES USING PRELIMINARY BUDGET

Run Conditions	Error Budget	RMS Position Errors (cm)			RMS Gravity Errors (sec)		(mgal)
		N	E	H	N	E	A
A. Baseline Run with preliminary budget for generating sensitivities.	Prelim.	15.8	13.6	13.2	.31	.26	1.3
B. Same as A. with 2 min. instead of 4 min. travel time.	Prelim.	9.8	8.9	8.8	.30	.25	1.1
C. Baseline Run with current budget 40 sec. ZUPT duration	Current	10.8	9.2	9.1	.14	.13	.64
D. Same as C. but 20 sec. instead of 40 sec. ZUPT duration	Current	12.9	11.4	11.1	.19	.18	.79
E. Same as C but 60 sec. instead of 40 sec. ZUPT duration	Current	9.0	8.1	8.0	.13	.11	.57
F. Same as C but .001 FPS ZUPT noise instead of .005 FPS	Current	10.1	8.5	8.3	.13	.12	.60
G. Same as C but .01 FPS ZUPT noise instead of .005 FPS	Current	12.3	10. 8	10.6	.17	.15	.73
H. Baseline with modified system budget	Modified	8.3	6.7	6.5	.11	.097	.51
I. Same as H with double traverse	Modified	7.0	5.9	5.8	.11	.096	.50

TABLE 6: SUMMARY OF SIMULATION RESULTS

brings further improvement to gravity measurement but it is not as significant. The better accuracy is due to a reduction in the standard deviation of the noise in inverse proportion to the square root of the length of the ZUPT duration.

6.5 Effect of ZUPT Velocity Uncertainty

All of the simulations made to investigate performance for the various error budgets assumed a ZUPT velocity uncertainty of .005 FPS. This error source being principally due to motion of the vehicle during ZUPT is more severe for the helicopter application. In field tests of IPS-2 on board a Bell 206B helicopter the standard deviation of the velocity error residual was computed and averaged about .005 FPS under mild weather conditions (low wind, etc.). To show the effect of a more severe environment, such as higher wind conditions, a run was made for a .01 FPS ZUPT uncertainty. Also a run was made for a .001 FPS value, representative of conditions with the IMU removed from the vehicle. The current error budget was used. Results are summarized in Table 6 (C,F,G). For a ten to one increase in velocity uncertainty, a 20 to 30 percent increase in gravity survey error occurs. A similar sensitivity occurs with position error. This result is valid only for the particular budget used and its relation to the velocity uncertainty values. However, ZUPT velocity uncertainty does not appear to be a major contributor to the overall system gravity survey error.

6.6 Simulation Run with Modified Error Budget

Since Honeywell is confident that these modifications can be incorporated in the future a simulation run was made using a modified error budget to show expected performance. Table 6 (H) shows a summary of the modified system. This budget will require review using new data once system modifications have been completed.

6.7 Double Traverse Runs

All previous runs have been single traverse runs. That is, the vehicle departed the initial control point and the traverse ended at a remote control point. In the case of the double traverse, the vehicle turns around at the remote control point and retraces the path approximately ending the traverse at the original initial control point. All data are then used by the Kalman smoothing to do the closure. A run was made to investigate the potential benefit of using a double traverse. The budget for the modified hardware configuration was used. The results are presented in Table 6 (I). Comparing the gravity survey results, the use of the double traverse only indicates about a 1 to 4 percent gravity measurement improvement. This amount of improvement would not justify the extra time and expense of the reverse traverse. The position results are 12 to 16 percent better, possibly significant for position work. An important consideration for evaluating the double traverse results is the modeling of the gravity errors. In this study a standard order Markov model is used with all three axes independent. If auto correlation information is present which will essentially tell the Kalman filter and smoother that the vehicle is retracing nearly the same pattern of gravity field changes, then a more substantial reduction in errors could be expected from a double traverse.

6.8 Simulation Results Summary

The runs made to provide IPS-2 error sensitivities show that accelerometer bias, scale factor errors and velocity random walk are the largest contributors to gravity survey errors. Reducing travel time has little impact on gravity survey accuracy although extending ZUPT duration from 20 to 40 seconds does give significant improvement. Likewise, the use of a double traverse, under current gravity modeling methods, shows little benefit. ZUPT velocity uncertainty below about .005 FPS had little impact on gravity accuracy. The simulations project vertical deflection accuracy of about .1 arc-sec rms and gravity anomaly accuracy of .5 mgal provided that changes are made to improve current IPS-2 hardware and software design, as well as procedural and data processing capabilities.

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